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A COMPARATIVE STUDY ON STRONG GROUND MOTION IN TWO VOLCANIC ENVIRONMENTS: AZORES AND ICELAND

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SUMMARY

The objective of this paper is to present the main results of a comparative study of strong ground motion on the Azores and Iceland. These islands are a super-structural part of the Mid Atlantic Ridge, which marks the boundary between the North-American Plate and the Eurasian Plate and creates a north-south oriented belt of seismic and volcanic activity. The tectonic environments are described and compared emphasising the similarities in the geological structure, including surface geology and its effects on strong ground motion. Furthermore, the seismicity of the Azores and Iceland is compared based on earthquake catalogues using statistical analysis. The strong-motion networks on the islands are described along with the strong-motion data used in the subsequent analysis. The strong-motion data are compared using statistical analysis. The main emphasis is put on attenuation of strong-motion data, characterised by root mean square acceleration and peak ground acceleration. The attenuation is also compared to some of the common attenuation relationships, used by the engineering community in Europe and America.

The main findings are that there are significant similarities between the tectonic environments of the Azores and Iceland. Furthermore, the similarities found in seismicity are statistically significant. The attenuation is characterised by rapid decay with increasing distance and high acceleration in the near source area. It is found that the same ground motion estimation models can be applied on the Azores and in Iceland. On the other hand, it is found that fitting of some of the commonly used attenuation relationships to the data is poor. The deviation is most apparent for large epicentral distances as well as in the near source area. This indicates that there may be significant regional differences in strong ground motion related to the tectonic environments and local geology.

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INTRODUCTION

Along the middle of the Atlantic Ocean a gigantic submarine mountain scarp rises from the ocean floor and extends almost the entire length of the ocean. This mountain range, called the Mid-Atlantic Ridge, owes its formation to plate movement. As the adjacent plates slowly move apart, leaving a rift in the crust, that marks the plate boundary, which results in intrusion of magma into the seafloor forming a new oceanic crust. The new crust formed to the west migrates westward, while the new crust formed to the east migrates eastward. As the magma is pressed upwards the result is frequently volcanic eruptions that form the mountain range. The Ridge is characterised by earthquake activity (see Figure 1) that culminates at transform faults and fracture zones.

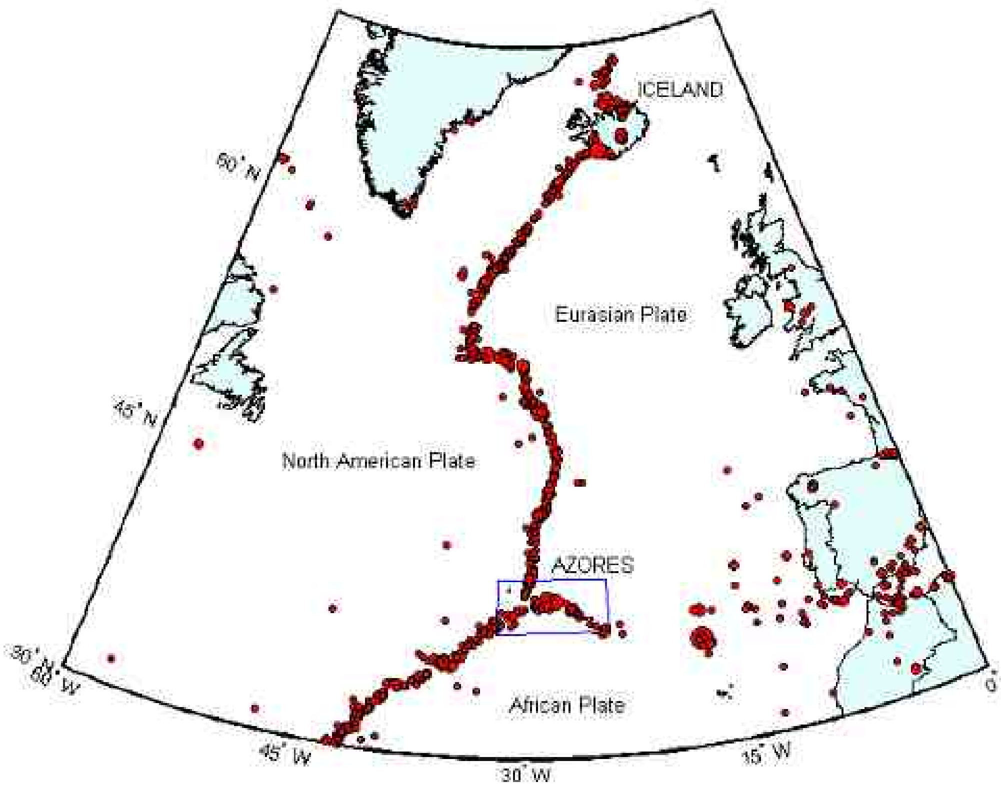

Figure 1: The northern part of the Mid-Atlantic Ridge is the borderline between the North American Plate on the on side and the Eurasian and the African Plate on the other. The red dots are earthquake epicentres.

Most of the Mid-Atlantic Ridge lies beneath the sea surface. In a few places it reaches above sea level and forms volcanic islands. The biggest of these islands is Iceland. It straddles the ridge and as new crust is formed along the rift zone, Iceland is increasing in size. Its western half is slowly moving westward on the North American plate and its eastern half to the east on the Eurasian plate. The Azores Islands are also a superstructural part of the Mid-Atlantic Ridge located at a triple junction between the North American, Eurasian and African Plate. These two volcanic environments are our study area.

The objective of our paper is to compare the strong ground motion on the Azores and Iceland. The main emphasis is put on comparison of peak ground acceleration and it is tested whether or not it is possible to apply same type of ground motion estimation models on both locations. Furthermore, the seismicity of the Azores and Iceland is compared based on preliminary earthquake catalogues using statistical analysis. The results presented are only the first part of an ongoing project.

Iceland

Iceland is located just south of the Arctic Circle in the middle of the North Atlantic Ocean, roughly between 63°N and 67°N latitude and 25°W to 13°W longitude (see Figure 1). The island covers an area approximately 500 km long from West to East and almost 400 km from South to North totally equal to 103,000 km^2. Around the main island there are numerous small islands, a few of which are inhabited. The geological environment of Iceland can be characterised as volcanic, volcanic activity being the main internal process forming the landscape. Still today the volcanic activity is rather high, with several major eruptions in the last century, the Vatnajökull eruption in 1996 being the last big one.

After human settlement, in the ninth century, almost 90 earthquakes of tectonic origin were experienced in Iceland, killing roughly 100 people and causing extensive damage and economic disruption. In the same period, numerous volcanic eruptions took place in Iceland. These eruptions caused only few direct casualties but the effects following in their wake were in many cases devastating.

The Azores

The Azores Islands are located in the North Atlantic Ocean, between 37° and 40° N latitude and 25° and 31° W longitude, placed along a narrow area that extends for about 600 km with a general WNW-ESE trend (Figure 3). It includes the Western Group (the Flores and Corvo Islands), the Central Group (the Terceira, Graciosa, Sao Jorge, Pico and Faial Islands) and the Eastern Group (the Sao Miguel and Santa Maria Islands and the Formigas Islets). All the Azores Islands are of volcanic nature and emerge from an anomalously shallow and rough topographic zone - the so-called “Azores Plateau” - that has a general triangular shape and depths of less than 2000 m (Figures 3 and 4). The Azores Plateau marks the transition to the nearby abyssal plains, with depths of over 3500 m.

After human settlement, in the 15th century, almost 30 earthquakes of tectonic origin were felt in Azores Islands with a maximum Modified Mercalli (MM) intensity higher than, or equal to, VII, killing about 4300 to 5300 people and causing important damage and economic disruption. In the same period, about 30 volcanic eruptions took place in the Azores region, causing almost 240 deaths, and characterised by different volcanic styles (from Hawaiian to Plinian or sub-Plinian type eruptions, including also Surtseyan activities).

The last volcanic eruption, lasting from late 1998 till the beginning 2000, took place in the sea, west of Terceira Island (“Serreta oceanic eruption”), and the last important earthquake occurred on July 9, 1998, off-shore Faial Island, with a moment magnitude M = 6.0 and intensity V1II-IX MM. This important event, together with the occurrence of other two strong damaging earthquakes, in 1973 and 1980 with epicentres in the Central Group, emphasised the need for a revision of the present seismic code which is based on hazard studies from late 1970 [40]. In that code, all islands, besides Flores and Corvo, are located in the zone of highest hazard.

Oliveira et al. [38] re-evaluated the seismic hazard for Sao Miguel Island, in terms of macroseismic intensity (MM scale), showing important differences within the island itself that recommend the introduction of a non-uniform zoning approach.

SEISMOTECTONICS OF THE ICELAND AND ICELAND REGION

Iceland, lying astride the Mid-Atlantic Ridge as a landmass between the submarine Reykjanes Ridge to the southwest and the Kolbeinsey Ridge to the north, has been geologically active during the last 20-25 million years. The island has been created by rifting and crust formation through volcanism in the rift zone, the volcanic zones, which mark the boundary between the Eurasian and North American plates. Accordingly, the western part of Iceland, west of the volcanic zones, belongs to the North American plate and the eastern part to the Eurasian plate. Crossing the island, the boundary is displaced eastward through two major fracture zones, one in the South, the South Iceland Seismic Zone, and another in the North, the so-called Tjörnes Fracture Zone, which extends far offshore (see Figure 2). A mantel plume rising under the island increases Iceland's geophysical complexity.

The earthquakes in Iceland may be divided into three main categories, reflecting the main sources of triggering:

- ✓ *Tectonic earthquakes* are due to relative movements of the North American and Eurasian Plates. These are the biggest earthquakes and may reach magnitude seven or even more.
- ✓ *Volcanic earthquakes* are attributable to volcanic activities as the main source of triggering. These earthquakes are generally located in the vicinity of well-known volcanoes, and their magnitude will rarely exceed six. This type of earthquake does not normally have any significant effect on structures.
- ✓ *Geothermal earthquakes*, usually not exceeding magnitude three, are small tremors occurring quite frequently in high-temperature geothermal areas. They do not have any significant effect on engineered structures, but can be annoying and disturbing to exposed people.

In addition to these naturally triggered earthquakes, the so-called man-made earthquakes should be mentioned to complete the picture. They are assigned primarily to the activities of man, e.g., the filling of reservoirs and rock blasting, and have been encountered a few times. In all cases to date, they have been small and insignificant.

The tectonic earthquakes in Iceland are of two types, i.e., interplate earthquakes, related directly to plate boundaries, and intraplate earthquakes originating inside the plates. The interplate earthquakes in Iceland can be divided into two groups, depending on the place of origin. In the first group, earthquakes originate in the spreading zone between the plates, i.e., on the Mid-Atlantic Ridge. These earthquakes are rather small, with magnitudes that seldom exceed five. The source mechanism can be complex. In the second group, earthquakes originate in the above-mentioned fracture zones. They are the biggest earthquakes in Iceland, and their source mechanism, obtained by fault plane solutions, is, in all cases, of a strike slip type.

The seismic motion projected for the South Iceland Seismic Zone on the basis of plate tectonics, which is left-lateral on the east-west striking fault, is, nevertheless, not visible on the surface as a surface fracture. It appears, on the contrary, that the motion can be visualised as a series of north-south striking, right-lateral faults. This is supported by the geological evidence of fault traces on the surface as well as by the north-south, elongated shape of the mapped destruction zones of large, historical earthquakes [6, 7, 8, 21]. In the northern seismic area, this is not as obvious since the epicentral areas are mostly beyond the coast. However, it is anticipated that the earthquakes in the northern zone can be modelled by a quite similar 'book-shelf' mechanism.

The intraplate earthquakes in Iceland are not as frequent as the interplate earthquakes. In this century, they have been recorded in the western part of the country [21]. Their mechanism seems to be complex.

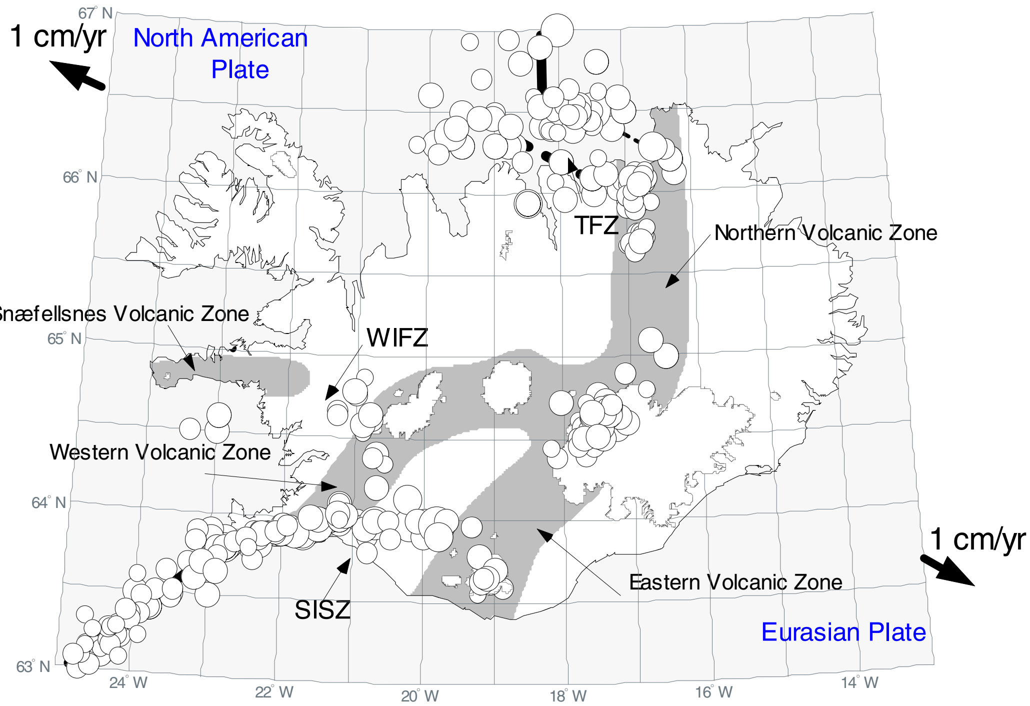

Figure 2: General tectonic framework of Iceland. The grey areas denote volcanic zones as well as rift zones on land, solid lines are rift zones offshore representing parts of the Mid-Atlantic Ridge, dashed lines indicate fracture zones and seismic lineation, the white circles indicate earthquake epicentres [1]. The following notation is used: SISZ is the South Iceland Seismic Zone, TFZ is the Tjörnes Fracture Zone, WIFZ is the West Iceland Fracture Zone.

Written documentation exists of earthquakes in Iceland in the last millennium. This information has been summarised in a pioneering work by Professor Thoroddsen [50, 51, 52]. In the XXth century, some important work has been carried out regarding this historic seismicity. Here it is especially worth mentioning the contributions by Tryggvason, Thoroddsen and Thórarinsson [53] and Björnsson and Einarsson in a series of papers (see for instance [6, 7, 8, 19, 20, 21]). Ambraseys and Sigbjörnsson [1] compiled available instrumental recordings in the period 1896 to 1996 and published a comprehensive earthquake catalogue for Iceland.

SEISMOTECTONICS OF THE AZORES REGION

The Azores region is located at the triple junction between the Eurasian, African and North American lithospheric plates, with islands aligned along major tectonic lineaments with a general WNW-ESE trend on the so-called Azores "microplate" or "block" [23, 28, 31, 43], an approximately triangular area with active volcanism and high seismicity (Figure 3). The location and nature of the northern and southern arms of the Azores triple junction correspond to the Mid-Atlantic Ridge (MAR), a pure distensive structure which is placed between the Flores and Faial Islands and constitutes the boundary between the North American plate and the other two plates, including the microplate (Figure 4).

The type and location of the third branch (the Azores-Gibraltar branch) is still controversial, in spite of several models proposed to explain the present kinematics of the Azores triple junction, especially in what concerns the Azores region itself [16]. However, in general terms the Azores-Gibraltar Fault System can be considered as the frontier among Eurasian and African plates, which presents three sectors with distinct geodynamic behaviour (Figures 3 and 4):

- ✓ an eastern sector (east of 15°W), with collision tectonics between the Eurasian plate and the African plate;
- ✓ a central sector, west of 15°W and 800 km long, that corresponds to a well-defined right-lateral strike-slip fault (e.g. Gloria Fault);
- ✓ a western branch (roughly between Santa Maria Island and the MAR), that acts as a leaky transform boundary, with oblique spreading.

Available data and the pattern of the seismic and volcanic activity point to the general idea that the Terceira Rift (Figure 4) acts as the western part of the third arm of the Azores triple junction. However, other important tectonic lineaments are present in the region, most of them with a WNW-ESE to W-E trend cutting the MAR. These are, from north to south (Figs. 1 and 2), the North Azores Fracture Zone (NAFZ), the Faial-Pico Fracture Zone (FPFZ), the Azores Bank Fracture Zone (ABFZ), the Princess Alice Bank Fracture Zone (PABFZ) and the West Azores Fracture Zone (WAFZ). While the last, non seismic zone, can be considered the extension of the East Azores Fracture Zone (EAFZ) to the west of the MAR, the FPFZ, displaying high seismicity and having clear bathymetric and magnetic expression, probably defines the location of the Azores triple point [28] at the intersection with the MAR.

The above-mentioned major tectonic lineaments and the local fault systems that cross the islands are responsible for an important seismic and volcanic activity, reported essentially for the Central Group and the Sao Miguel Islands [30]. Since 1980 the installation, in the Azores, of a telemetric seismological network as well as digital stations (after 1997) on several islands [47], has significantly increased the perceptibility of earthquake activity, recording hundreds of microearthquakes each year and pointing out the major seismogenic areas of the archipelago. In fact, most of the earthquakes are located on the Terceira Rift, the FPFZ, the MAR and associated areas, such as the D. Joao de Castro submarine volcano (between the Terceira and Sao Miguel Islands) or the Povoacao Trough (to the SE of Sao Miguel Island).

Similarly to the situation in Iceland, the earthquakes in the Azores Region may also be divided into the three main categories, *Tectonic*, *Volcanic* and *Geothermal earthquakes*, essentially with the same characteristics.

SEISMICITY AND EARTHQUAKE CATALOGUES

There are obvious strong similarities of the two tectonic environments described. However, it is not evident that the seismicity of the Iceland and the Iceland Region, on one hand, and the Azores Region, on the other, is of comparable scale. We have tried to make a comparison based on existing earthquake catalogues, which unfortunately are not complete. The earthquake catalogue for the Azores is currently undergoing a major revision. We have therefore based our comparison on available information [16]. Ambraseys and Sigbjörnsson [1] have re-assessed the magnitudes of Icelandic earthquakes based on teleseismic data. There are obvious difficulties in comparing these catalogue data and we should therefore treat the results with some precaution.

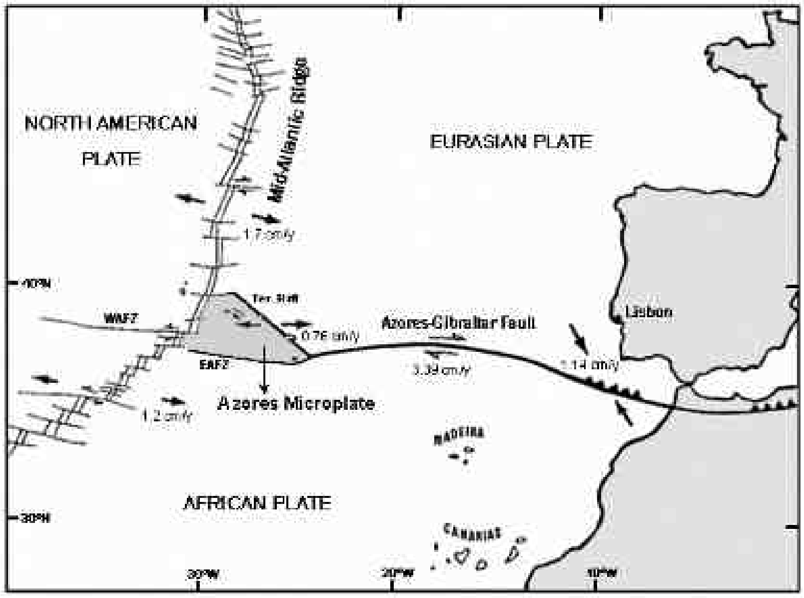

Figure 3: General geotectonic framework of Azores archipelago (after Forjaz, 1983 and Buforn et al., 1988; in: Nunes, 1999). Displacement rates in Nunes, 1991. WAFZ – West Azores Fracture Zone; EAFZ – East Azores Fracture Zone; Ter. Rift – Terceira Rift.

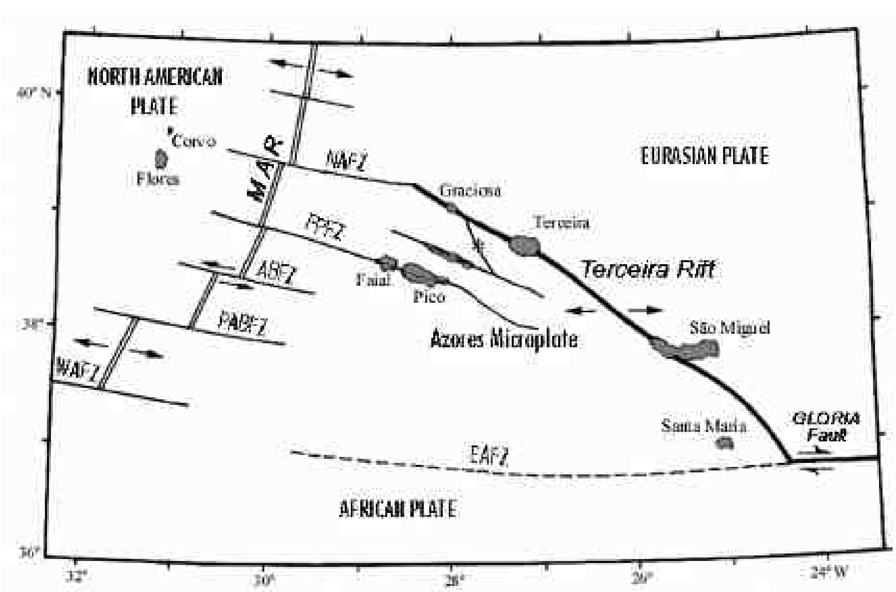

Figure 4: Location of islands and main tectonic lineaments of Azores triple junction (in: Nunes, 1999). Asterisk shows the location of 1st January, 1980 earthquake. MAR – Mid-Atlantic Ridge; NAFZ – North Azores Fracture Zone; FPFZ – Faial-Pico Fracture Zone; ABFZ – Açor Bank Fracture Zone; PABFZ – Princess Alice Bank Fracture Zone; WAFZ – West Azores Fracture Zone; EAFZ – East Azores Fracture Zone.

There are obvious similar upper bounds on magnitude to be expected in these two regions, that is magnitude 7.2 on surface-wave magnitude scale. This is based on available instrumental data covering roughly the last one hundred years, i.e. the period after 1896. To investigate the significance of the difference between the two earthquake populations, as represented in the aforementioned catalogues, we have used Kolmogorov-Smirnov test.

The comparison is based on the difference between the sample distributions for earthquake magnitude greater than 6, as we judge that the magnitudes above that value are reasonably reliable. The result is that there is not a statistically significant difference between the earthquakes in these two regions as far as inferred from the sample distributions for earthquakes of magnitude above 6. More in-depth comparative statistical study of the catalogues is, however, needed.

It was noted in the introduction that the number of casualties due to earthquakes are much lower in Iceland than on the Azores. This may seem a contradiction as the maximum earthquake magnitude and magnitude distributions for the destructive earthquakes are comparable, in addition the corresponding intensity assessments give us equivalent figures. We believe that the reason may be: (1) different building traditions, and (2) variability in population distribution within the most earthquake prone areas. Another reason may come from the exaggerated number of victims in prior to XIXth century occurrences.

GROUND MOTION ESTIMATION EQUATIONS

Azores

Before the creation, in 1995, of the "Azores Digital Strong Motion Network" only a few acceleration analogical records had been obtained at the archipelago [37]: three during the 1973 Pico island seismic crises with a maximum duration magnitude M_d = 5.6 [30], the other for the Terceira, 1980 earthquake, with **M** = 7.2, and the last for the Faial, July 9, 1998 earthquake with **M** = 6.0 [39]. The first event recorded at the digital accelerographic network was the January 5th, 1996, earthquake with **M** = 3.9. Since then this network was improved and extended to São Miguel and the Central Group islands, and includes presently 15 strong motions stations, some connected by modem to a central unit.

A first attempt to derive PGA attenuation laws for Azores islands [38] was recently made but the compiled instrumental data is still scarce, mainly in the range of higher magnitudes. Therefore, a trial computation of seismic hazard was carried out using the Boore et al. attenuation law [9]. This ground motion estimation equation accounts for different types of soil conditions, a parameter to consider in a future development, and was found, at that time, to be the most suitable when fitted to PGA data of the Azores network. The fit was, however, not very satisfactory indicating generally faster attenuation than predicted by the model.

The events recorded up to now are small to moderate sized, with few exceptions. The peak ground acceleration obtained during a few of the higher magnitude events at the archipelago are plotted on Figure 5 along with some Icelandic data and a ground motion estimation model derived by Olafsson on the basis of the Brune spectral models [36]. The fit appears more satisfactory than in earlier studies [16]. It is worth noting the high horizontal PGA values ($\cong$ 390 cm/s^2) recorded during the July 9th, 1998 Faial/Pico/São Jorge earthquake (**M** = 6.0) at a station located 14.4 km away from the epicentre. This value was obtained at the Prince of Monaco Observatory located on the top of a scoria cone in Horta town (Faial island). Studies carried out on topographic effects of this cone are still inconclusive [27] and, therefore, cannot be used to correct those high PGA values. Recent studies [24] made with data from the Seismological network indicate a systematic deviation in this location of 25% to 40% above average for the horizontal components.

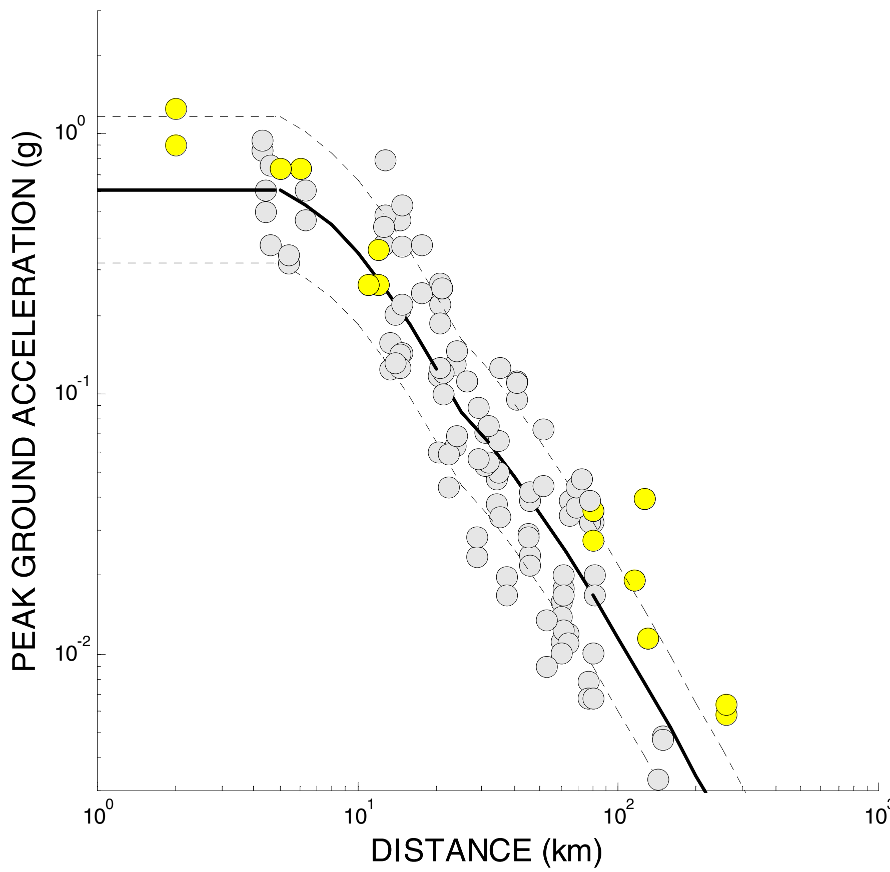

Figure 5: Suggested ground motion estimation equation (solid black line) plotted with strong-motion data. Peak ground accelerations in Azores (yellow dots) and in Iceland (grey dots). Earthquakes included are: 23 November 1973, 01:36 (Azores); 1 January 1980, 04:43 (Azores); 9 July 1998, 05:19 (Azores); 17 June 2000, 15:41 (South Iceland); 17 June 2000, 15:43 (South Iceland); and 21 June 2000, 00:52 (South Iceland). The data applied have been extracted from the ISESD Website and scaled to magnitude 6.6.

Iceland

The Icelandic Strong-Motion Network was established in the early eighties [46]. Up to now it has recorded more than 300 earthquakes, some of which are noteworthy. In June 2000 the South Iceland Lowland was hit by a devastating earthquake sequence. The biggest events in this sequence were recorded on 17 June and 21 June. In the June 2000 earthquake sequence, about 80 events where recorded on the Icelandic Strong-Motion Network, resulting in about 750 ground response time series. Further information on these earthquakes can be found in [45].

The attenuation of ground motion in Iceland has been reported in series of papers. The first attempt was carried out by Sigbjörnsson [46], followed by important studies headed by Olafsson [32, 33, 34, 36]. The result of this work is summarised in Figure 5 showing a ground motion estimation model (see [45] for further details) plotted along with South Iceland earthquake data as well as data from the Azores.

This figure shows the same main trend as observed earlier, that the Icelandic data and the data from the Azores, attenuate more or less in the same way. In this context it is worth noting that the same basic data is applied for all earthquakes, which is probably an oversimplification.

DISCUSION AND CONCLUSION

The main findings are that there are significant similarities between the tectonic environments of the Azores and Iceland. Furthermore, the similarities found in seismicity are statistically significant. The attenuation is characterised by rapid decay with increasing distance and high acceleration in the near source area. It is found that the same ground motion estimation model can be applied on the Azores and in Iceland. On the other hand, it is found that fitting of some of the commonly used attenuation relationships to the data is poor. The deviation is most apparent for large epicentral distances as well as in the near source area. This indicates that there may be significant regional differences in strong ground motion related to the tectonic environments and local geology.

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